PATTERNING METHODS AND SYSTEMS USING REFLECTED INTERFERENCE PATTERNS

Related Applications

The present application claims priority from U.S. Provisional Application Serial No. 60/185,288 filed February 28, 2000, the disclosure of which is hereby incorporated herein in its entirety by reference.

Background of the Invention

The present invention relates to the field of microelectronics and more particularly to microelectronic patterning.

As integrated circuit devices become more highly integrated, dimensions of structures such as conductive lines and via holes and spaces therebetween are reduced. Accordingly, patterning processes are needed for smaller patterns. In the past, conventional optical lithography techniques have been used.

In optical lithography, an image of a pattern is optically projected onto a substrate by transmitting radiation through a mask including the pattern thereon. In essence, a pattern from a mask is projected onto a photosensitive material which is then developed so that the developed photosensitive material has the pattern of the mask. As the dimensions of microelectronic structures are further reduced, however, mask projection techniques may limit further reductions in pattern sizes.

Accordingly, there continues to exist a need in the art for improved patterning methods and systems.

Summary of the Invention

According to embodiments of the present invention, a layer on a substrate can be patterned using interference patterns. For example, coherent radiation can be projected toward a reflector surface so that the coherent radiation is reflected off the reflector surface to provide a holographic projection of a desired image wherein the reflector surface includes information that corresponds to an inverse of the holographic projection of the

desired image. The substrate including the layer can be maintained in the path of the reflected radiation so that the interference pattern is projected onto the layer. Accordingly, the holographic projection of the desired image can be used to patter the layer. For example, after maintaining the substrate including the layer in the path of the reflected radiation, the layer can be developed so that portions thereof are maintained and removed according to the intensity of the holographic projection of the desired image projected thereon.

Methods and systems according to embodiments of the present invention can thus provide patterning for microelectronic structures having relatively fine dimensions. Moreover, defect tolerance can be increased because the effect of a defect on the reflector surface is distributed throughout the interference pattern projected onto the surface of the layer being patterned.

Brief Description of the Drawings

Figure 1 is a block diagram of a reflective holographic microscope.

Figure 2A is a cross-sectional view of a sphere on a silicon substrate subjected to coherent radiation.

Figure 2B is a hologram computed using the coherent radiation of Figure 2A.

Figure 3A is a cross-sectional view of two spheres on a silicon substrate subjected to coherent radiation.

Figure 3B is a hologram computed using the coherent radiation of Figure 3A.

Figure 4A is a cross-sectional view of one sphere on a second sphere on a silicon substrate subjected to coherent radiation.

Figure 4B is a hologram computed using the coherent radiation of Figure 4A.

Figure 5A is a cross-sectional view of a cube on a silicon substrate subjected to coherent radiation.

Figure 5B is a hologram computed using the coherent radiation of Figure 5A.

Figure 6 is a block diagram of a reflective holographic microscope including a laser.

Figure 7 is a reconstructed image generated using off-axis holography.

Figure 8 is a block diagram of a patterning system.

Figure 9 is a cross sectional view of a reflector including a plurality of topographical features.

Figure 10 is a block diagram of a patterning system including a plurality of radiation sources.

Figure 11 is a block diagram of a patterning system including a plurality of patterning reflectors and a plurality of reflectors.

Figure 12 is a block diagram of a patterning system including a filter.

<u>Detailed Description</u>

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

It will be understood that when an element such as a layer, region, or substrate is referred to as being “on” another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being “connected” or “coupled” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, there are no intervening elements present. In the drawings, the dimensions of layers and regions are exaggerated for clarity.

A block diagram illustrating a reflective holographic microscope **31** and methods used to characterize a sample surface **41** is shown in Figure 1. As shown, the microscope can include a source of coherent radiation **33**, a detector **35**, a controller **37**, and an output device **39**. The radiation source **33** projects coherent radiation **34** along divergent paths toward the sample surface **41** so that the coherent radiation is reflected or scattered off the sample surface **41**. The detector **35** defines an interference plane **36** to detect an interference pattern generated by the reflected and unreflected portions of the coherent radiation **34** incident on the interference plane. In particular, the detector may detect both amplitude and phase information of radiation incident on the interference plane **36** to provide a measurement of an interferogram or Fresnel hologram resulting from interference of the reflected and unreflected portions of the coherent radiation at the interference plane. For example, the detector **35** may be a charge coupled device (CCD) that generates a digital representation of the radiation incident on the interference plane. Alternately, other detectors known now or developed in the future may be used.

Measurements of the reflected and unreflected portions of the coherent radiation can then be provided by the detector **35** to the controller **37**. The controller can use the amplitude and phase information included in these measurements to reconstruct a three-dimensional image of the sample surface **41**. The three-dimensional image can be displayed on an output device **39** such as a CRT or LCD screen or a printer. Alternately or in addition, the controller can use the amplitude and phase information to make measurements of particular features of the sample surface. As shown in Figure 1, the sample surface may include a raised portion **43** such as a gate electrode, a conductive line, or an isolation region, and it may be desirable to determine a width of the raised portion **43**. The controller can use the amplitude and phase information to determine a width of the raised portion. In addition, heights and/or shapes of raised portions can be determined. Alternately or in addition, widths, depths, and/or shapes of trenches or holes can be determined.

The controller can use geometric calculations based on the amplitude and phase information to reconstruct the three-dimensional image of the sample surface. As will be understood by those having skill in the art, the controller can be implemented using special purpose hardware-based systems, general purpose computer systems together with computer instructions, and/or combinations of special purpose and general purpose systems. As will be further understood, the controller can be implemented using one or more integrated circuit devices, combinations of discrete circuit devices, and/or combinations of discrete and integrated circuit devices. Moreover, while the detector **35** and the controller **37** are illustrated as separate blocks in Figure 1, it will be understood that the detector could be implemented as a portion of the controller, or the detector could be implemented as a separate block including functionality discussed above as being performed by the controller. The controller **37** can also be used to maintain relative positions of the radiation source **33**, the sample surface **41**, and the detector **35**.

According to a particular embodiment of the present invention, the radiation source **33** can project a coherent beam of electrons. For example, the radiation source **33** can be a field emitter that emits an electron beam in response to a voltage applied thereto. In particular, the radiation source can be a nanotip field emitter wherein the tip has dimensions on the order of an atom. By providing a nanotip with these dimensions, a coherent electron beam can be generated by applying a voltage difference between the radiation source and the sample surface **41**.

The preparation of a single-atom tip from W [111]-oriented single crystal wires is discussed, for example, in the reference by Hans-Werner Fink et al. entitled *State Of The Art Of Low-Energy Electron Holography*, Electron Holography, A. Tonomura et al. (Editors), Elsevier Science B.V., 1995. The Fink et al. reference also discusses the generation of a beam of coherent electrons using the single-atom tip. The Fink et al. reference is hereby incorporated herein in its entirety by reference. The voltage difference between the radiation source **33** and the sample surface **41** can be generated

using the controller **37** as shown in Figure 1. According to another example, a nanotip could be provided using a carbon nanotube.

A reflective holographic microscope can be provided, for example, by fitting a nanotip emitter into a scanning electron microscope (SEM) such as a Hitachi CD-SEM. Using a tungsten nanotip emitter as discussed in the Fink et al. reference, for example, an effective tip radius of less than 3nm can be provided, and turn on energies can be provided in the range of 60V to 100V. The resulting emission current can be varied from less than 1nA to nearly 1μA for extraction voltages in the range of 60V to 500V, and a brightness of 10^7 Amp/cm^2/str. at 500eV can be provided. Moreover, an emission stability of less than 5% can be provided at a pressure of 10^{-8} torr for over a one minute period.

According to a particular example of the present invention, a relatively low energy of less than 100eV can be applied between the radiation source **33** and the sample surface **41** to generate the divergent beam **34** of coherent electrons. The divergent beam **34** can thus provide an illumination footprint in the range of 20μm to 30μm in diameter on the sample surface. The electrons in the divergent beam **34** are elastically scattered at the sample surface **41** by reflection from the inner potential of the sample, and reflected (scattered) and unreflected (unscattered) portions of the divergent beam interfere to provide the interferogram (Fresnel hologram) at the interference plane **36**. Because the interference plane is provided downstream from the radiation source **33**, the resulting hologram can be referred to as a forward scatter hologram.

Because the resolution of an electron hologram is determined by the wavelength of the electrons used to form the hologram, very high resolutions can be provided. In particular, a resolution on the order of three times the wavelength of the electrons can be provided. Accordingly, a resolution of less than one nanometer may be possible using an electron beam energy of 50eV. Moreover, there may be little or no diffraction limit because the incident beam is divergent. In addition, lens aberrations and/or distortions can be reduced or eliminated because no lenses are required.

Radiation damage to the sample surface and charging of the sample surface can be reduced when compared to systems such as a scanning electron microscope. First, the damage and charging can be reduced because the electron beam can be generated using relatively low energies of less than 100eV. Second, the damage and charging can be reduced because the divergent beam is spread over a relatively wide area as compared to more focused beams used in scanning electron microscopes. An additional potential advantage of the reflective holographic microscope of Figure 1 is that the hologram can be a more robust format for data than a conventional image because the resulting phase and amplitude information can provide more information. Furthermore, the reflective holographic microscope of Figure 1 does not require focusing, and a wide range of magnifications can be provided without significant adjustment.

While examples of reflective holographic microscopes and methods of Figure 1 are discussed as including a radiation source that generates a divergent beam of coherent electrons to provide an electron hologram, other sources of radiation may be used. For example, a laser can be used to provide a divergent beam of coherent light.

As discussed above with regard to Figure 1, reflective holographic microscopes and methods can be used to generate images of and/or measure dimensions of a surface feature of a sample. A reflective holographic microscope can thus be used for critical dimension (CD) metrology for microelectronic processing to verify sizes and spacings of microelectronic structures.

A reflective holographic microscope can also be used for defect detection in microelectronic processing. In general, an interference pattern generated by a defect such as a particle will be distinct with respect to an interference pattern generated by an intended microelectronic structure such as a gate electrode or a conductive line. Accordingly, a reflective holographic microscope can be used to detect defects and provide a measure of a defect density. Figures 2-5 illustrate examples of holograms produced by a

particle(s) on a smooth substrate when analyzed using a reflective holographic microscope.

In Figure 2A, a single 5nm sphere **45** on the surface of a silicon wafer **47** subjected to coherent electron beam **49** at 50eV can generate the computed hologram **51** with 100X100 pixels shown in Figure 2B. As discussed above, the hologram is an interference pattern of reflected and unreflected components of the coherent radiation **34**. The hologram generally is not an image, so reconstruction is needed to generate an image of the sphere. A spherical particle defect on a silicon wafer would thus produce a similar interference pattern which could be readily identified to determine a defect density.

In Figure 3A, two 5nm spheres **55A** and **55B** are on a silicon substrate **57** spaced by 5nm. The two 5nm spheres can be subjected to coherent electron beam **59** at 50eV to generate the computed hologram **61** shown in Figure 3B. The extra fringes carry information that can be used to determine the spacing and relative positions of the two spheres. Two spherical particle defects on a silicon wafer would thus produce a similar interference pattern.

In Figure 4A, two 5nm spheres **65A** and **65B** are placed 5nm apart, one above the other with respect to a silicon substrate **67**. The two 5nm spheres can be subjected to coherent electron beam **69** to generate the computed hologram **71** shown in Figure 4B. In Figure 5A, a 5nm cube **75** on a silicon substrate **77** can be subjected to coherent electron beam **79** to generate the computed hologram **81** shown in Figure 5B. As shown in Figures 2-5, holograms generated using a coherent electron beam can be used to identify, characterize, and/or quantify defects on a substrate surface.

A reflective holographic microscope **91**, using a laser **92** as a source of coherent radiation, is illustrated in Figure 6. In particular, a divergent beam of coherent radiation **94** can be generated using laser **92** and short focal length lens **93**. Portions of the divergent beam of coherent radiation **94** reflect off the sample surface **101** including the raised portion **103**, and reflected and unreflected portions provide an interferogram or hologram at the interference plane **96** of the detector **95**. The detector **95** provides a measure of the

interferogram to the controller **97** which can reconstruct a three-dimensional image of the sample surface. The three-dimensional image can be provided on the output device **99**, and the laser **92** can operate responsive to the controller **97**.

Figure 7 illustrates a reconstructed image generated by a point projection microscope as discussed above. More particularly, the image of Figure 7 is a three dimensional reconstruction of approximately 100nm features on a SCALPEL mask performed using off-axis holography.

While reflective holographic microscopes have been discussed with respect to coherent radiation such as coherent electron and laser beams, it will be understood that any form of coherent radiation can be used in reflective holographic microscopes.

Interference patterns can also be used to provide patterning for microelectronic structures. Examples of systems and methods using interference patterns for patterning are illustrated in Figure 8. As shown, a patterning system **131** can be used to pattern a layer **151** of a microelectronic structure **153**. In particular, the patterning system can include a source of coherent radiation **133**, a patterning reflector having a surface **141**, and a controller **137**. The radiation source **133** generates a divergent beam of coherent radiation **134**, portions of which are reflected off the surface **141** of the patterning reflector wherein the surface **141** includes information that corresponds to an inverse holographic projection used to pattern the layer **151**. Portions of the coherent radiation can also be transmitted to the layer **151** without reflecting off the reflector surface **141** to interfere with the portions of the coherent radiation reflected off the reflector surface.

The layer **151** to be patterned is placed in the path of reflected and unreflected portions of the coherent radiation **134** to define an interference plane. Accordingly, a Frenel hologram or interferogram can be defined on the layer **151** as reflected and unreflected portions of the coherent radiation **134** interfere at the layer **151**. Portions of the layer **151** can be selectively maintained and removed depending on the intensity of the hologram thereon. For example, the layer **151** can be a layer of a photosensitive material, such

as photoresist, that can be chemically developed so that portions thereof are removed or maintained depending on the intensity of the radiation interference pattern incident thereon. The patterned photoresist can then be used as a patterning mask to selective etch an underlying layer of a device functional material.

Alternately, the patterning system **131** can be used to directly pattern a layer of a device functional material without using a photoresist layer. For example, the layer **151** can be a layer of silicon oxide (or other device functional material) on the order of two atoms thick, and portions of the silicon oxide layer can be removed by relatively high intensity portions of the hologram or interferogram formed thereon. The surface **141** of the patterning reflector thus determines the hologram or interferogram formed on the layer **151**, so that different surface patterns of the patterning reflector can be used to define different patterns in the layer **151**.

The cross-sectional view of the patterning reflector surface **141** illustrated in Figure 8 is provided by way of example with a single topographical feature to show how the divergent beam of coherent radiation **134** can react with features of the reflector surface **141**. It will be understood, however, that a reflector surface **141'** for the patterning system can have numerous topographical features **141A'-D'** of different shapes as shown in Figure 9. Moreover, the numerous topographical features can be arranged in various patterns such as dots and/or circles across the reflector surface.

While the reflector surfaces **141** and **141'** are shown with topographical features being used to generate interference patterns, other characteristics of reflector surfaces can be used to generate a desired interference pattern. For example, the reflector surface may be provided with areas of differing reflective/absorption properties; areas of differing compositional density; areas of differing electrostatic properties; areas of differing magnetic properties; and/or areas of differing topology. More generally, any variation in properties of the reflector surface that provide different reflective properties can be used to generate the interference pattern.

By way of example, an intensity distribution across a beam of coherent radiation projected toward the reflector surface can be arbitrarily adjusted by generating an interference pattern with a bi-prism or other electrostatic or magnetic devices. The intensity and phase information in the patterning wave front will depend on the interaction of an unreflected portion of the coherent beam transmitted directly from the source **133** to the layer **151** and a portion of the coherent beam reflected off the reflector surface. The patterning wave front at the layer **151** contains specific spatial and structural information to be transformed into specific two-dimensional and/or three-dimensional structures on the layer **151**. Accordingly, the reflective surface contains sufficient information, such that when the coherent beam reflects off the reflecting surface and interferes with a non-reflected portion of the coherent beam, an image can be patterned into the layer **151**, whether the layer **151** is a photoresist or a device functional material such as, for example, silicon, an oxide, a nitride, or a metal.

The substrate surface including the layer **151** can be maintained in the path of the reflected radiation so that the interference pattern is projected onto the substrate surface including the layer. After maintaining the substrate surface including the layer in the path of the reflected and non-reflected radiation, the layer can be developed so that portions thereof are maintained and removed according to the intensity of the interference pattern thereon.

As will be understood by those having skill in the art, the controller can be implemented using special purpose hardware-based systems, general purpose computer systems together with computer instructions, and/or combinations of special purpose and general purpose systems. As will be further understood, the controller can be implemented using one or more integrated circuit devices, combinations of discrete circuit devices, and/or combinations of discrete and integrated circuit devices. The controller can also be used to maintain relative positions of the radiation source **133**, the reflector surface **141**, and the microelectronic structure **153**.

According to a particular example of Figure 8, the radiation source **133** can project a coherent beam of electrons. For example, the radiation source

can be a field emitter that emits an electron beam in response to a voltage applied thereto. In particular, the radiation source can be a nanotip field emitter wherein the tip has dimensions on the order of an atom. By providing a nanotip with these dimensions, a coherent electron beam can be generated by applying a voltage difference between the radiation source and the reflector surface **141**.

The preparation of a single-atom tip from W [111]-oriented single crystal wires is discussed, for example, in the reference by Hans-Werner Fink et al. entitled *State Of The Art Of Low-Energy Electron Holography*, Electron Holography, A. Tonomura et al. (Editors), Elsevier Science B.V., 1995. The Fink et al. reference also discusses the generation of a beam of coherent electrons using the single-atom tip. The Fink et al. reference is hereby incorporated herein in its entirety by reference. The voltage difference between the radiation source **133** and the sample surface **141** can be generated using the controller **137** as shown in Figure 8. According to another example, a nanotip could be provided using a carbon nanotube.

A relatively low energy of less than 100eV can be applied between the radiation source **133** and the sample surface **141** to generate the divergent the divergent beam **134** of coherent electrons. The electrons in the divergent beam **134** are elastically scattered at the reflector surface **141** by reflection from the inner potential of the surface, and reflected (scattered) and unreflected (unscattered) portions of the divergent beam interfere to provide the interference pattern (such as an interferogram or Frenel hologram) at the layer **151** being patterned. Because the interference pattern is generated downstream from the radiation source **133** the resulting interference pattern can be referred to a forward scatter hologram.

Because the resolution of an electron hologram is determined by the wavelength of the electrons used to form the hologram, very high resolution can be provided. In particular, resolution on the order of thee times the wavelength of the electrons can be provided. Accordingly, a resolution of less than one nanometer may be possible using an electron beam energy of 50eV. Moreover, there may be little or no diffraction limit because the incident beam

is divergent. In addition, lens aberrations and/or distortions can be reduced or eliminated because no lenses are required.

While examples of a patterning system and methods of Figure 8 are discussed as including a radiation source that generates a divergent beam of coherent electrons to provide an electron hologram, other sources of radiation may be used. For example, a laser can be used to provide a divergent beam of coherent light. According to this example, the radiation source might include a laser and a short focal length lens to provide a divergent beam of coherent radiation.

Patterning using interference patterns as discussed above may provide tolerance to defects on the reflecting surface **141**. Defects in the reflecting surface **141** are expected to exhibit structures and signatures in Fourier space different than the structures and signatures of the intended pattern. These defect signatures can thus be separated and/or filtered in Fourier space. Moreover, any defect information may be convolved with the entire set of phase and amplitude information that impinges on the imaged layer **151**. Accordingly, defect information may be diluted across the imaged surface. Accordingly, in the transformation from reflector information to imaged information, small defects on the reflector surface **141** may not print on the layer **151**. Methods and systems according to embodiments of the present invention can thus provide defect tolerant patterning for microelectronic structures with relatively fine dimensions.

A controller **137** can be used to control the duration and intensity of the coherent radiation **134**. The controller can also be used to maintain relative positions of the radiation source **133**, the reflector surface **141**, and the microelectronic structure **153**. As discussed above with regard to the microscope of Figures 1 and 6, the radiation source **133** can be an electron emitter, a laser, or source of other coherent radiation.

Alternate reflective patterning methods and systems **331** are illustrated in Figure 10 including a reflector surface **341**, a plurality of radiation sources **333A-B**, and a controller **337** used to pattern layer **351** of substrate **353**. As shown, the reflective patterning system **331** may include a plurality of

radiation sources **333A-B** to generate a corresponding plurality of beams of coherent radiation **334A-B**. Portions of each of the beams of coherent radiation are transmitted directly to the layer **351** to be patterned, and portions of the beams are reflected off the reflector surface **341** to the layer **351**. With a plurality of radiation sources, each radiation source can be used to transmit different information to pattern the layer **351**, and/or the intensity of the interference pattern(s) at the layer **351** can be increased to increase throughput.

Additional reflective patterning methods and systems **441** are illustrated in Figure 11 including a plurality of reflector surfaces **441A-B**, a plurality of radiation sources **433A-B**, and a controller **437** used to pattern layer **451** of substrate **453**. As shown, the reflective patterning system **431** may include a plurality of radiation sources **433A-B** to generate a corresponding plurality of beams of coherent radiation **434A-B**. Portions of each of the beams of coherent radiation are transmitted directly to the layer **451** to be patterned, and portions of the beams are reflected off the respective reflector surfaces **441A-B** to the layer **451**. With a plurality of radiation sources and reflectors, each combination of radiation source and reflector can be used to transmit different information to pattern the layer **451**, and/or the intensity of the interference pattern(s) at the layer **451** can be increased to increase throughput.

Yet other reflective patterning methods and systems **541** are illustrated in Figure 11 including a reflector surface **541**, a radiation source **533A-B**, a filter **555**, and a controller **537** used to pattern layer **551** of substrate **553**. As shown, the reflective patterning system **531** may include a radiation source **533** to generate a beam of coherent radiation **534**. Portions of the beam of coherent radiation are transmitted directly to the layer **451** to be patterned, and portions of the beam are reflected off the reflector surface **541** to the layer **551**. More particularly, portions of the beam reflected off the reflector surface **541** to the layer **551** can be transmitted though filter **555** to reduce the generation of defects in the layer **551** being patterned resulting from defects in the reflector surface **541**.

As discussed above, defects in the reflector surface can be expected to have structures and signatures in Fourier space different than those of the desired patterns in the reflector surface. Accordingly, the filter **555** can separate and/or filter defect signatures in reflected portions of the beam to reduce resulting defects in the layer being patterned. The filter, for example, can be an electrostatic or electromagnetic filter that shapes the reflected portions of an electron beam to reduce defect signatures. If the radiation beam is an optical beam, the filter can be an optical lens. Moreover, filters can be used in patterning systems including multiple radiation sources and/or reflector surfaces. The system of Figure 10, for example, could include one or more such filters to filter radiation reflected from the reflector surface toward the layer **351**. The system of Figure 11 could include one or more filters between each of the reflector surfaces and the layer **451**.

In addition, the patterning methods and systems of Figures 8, 10, 11 and 12 may be configured to accept different reflectors to allow patterning of different layers and/or devices. In other words, a first reflector(s) could be used to pattern on first layer of a device and a second reflector(s) could be used to pattern a second layer of the same device. Alternatively, a first reflector(s) could be used to pattern a first layer of a first device, and a second reflector(s) could be used to pattern a second layer of a second device.

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.